PHENIX SPIN PROGRAM, RECENT RESULTS

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Acceleration of polarized protons in the Relativistic Heavy Ion Collider (RHIC) provides a unique tool to study the spin structure of the nucleon. We give a brief overview of the PHENIX program to investigate the unknown gluon and flavor decomposed sea quark polarization in the proton, utilizing polarized proton collisions at RHIC. We report first results from the PHENIX experiment on transverse single-spin asymmetry in π^0 and charged hadron production and longitudinal double-spin asymmetry in π^0 production, at mid-rapidity.

1 Introduction

Spin is one of the most fundamental properties of the elementary particles. The spin of the proton had been believed to be carried by the valence quarks for long years. From polarized deep inelastic (DIS) lepton-nucleon scattering experiments over the past 20 years it has been found that on average little of the proton spin is carried by quarks and antiquarks [1]. Therefore, most of the proton spin must be carried by the gluons and orbital angular momentum. It may also indicate that the sea quark polarization is large and anti-parallel to the proton spin.

DIS experiments have constrained the possible gluon polarization in the proton through the measurement of scaling violation in inclusive polarized scattering [2], and through semi-inclusive measurements of two hadrons to isolate the photon-gluon fusion diagram [3]. However, the reach of these measurements has been limited, due to the low energy available for fixed target experiments, and due to luminosity limitations. A fixed target experiment at Fermilab first presented a measurement with strongly interacting probes [4], again with limited sensitivity due to the fixed target energy and available luminosity. At this time, the gluon contribution to the proton spin is largely unknown.

The colliding polarized proton beams at the Relativistic Heavy Ion Collider provide a new laboratory to probe the proton spin structure with strongly interacting probes. There are several processes where gluons participate directly, such as prompt photon and heavy quark production. Flavor decomposition of quark and antiquark polarization can be done using W production. These measurements use longitudinal beam polarization.

Surprisingly large transverse single-spin asymmetries (A_N) have been observed in a number of experiments [5,6,7], ranging in energy $\sqrt{s}$=20–200 GeV. PHENIX will further investigate the origin of such asymmetries, colliding transversely polarized protons.

2 PHENIX spin program, recent results

2.1 Gluon polarization

Measurement of the gluon polarization (Δg) in a polarized proton is a major goal of the PHENIX spin program. The main probes are high p_T prompt photon production, jet (or leading hadron) production and heavy-flavor production.

The PHENIX experiment [8] has reported the unpolarized cross section for π^0 and prompt photon production in pp collisions at midrapidity, which is described well by next-to-leading order perturbative QCD (NLO pQCD) calculations [9,10]. In pQCD the longitudinal double spin asymmetry A_{LL} for those processes is directly sensitive to the polarized gluon distribution function in the proton [11,12,13]. A_{LL} is defined:

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \tag{1}$$

where σ_{++} (σ_{+-}) is the cross section of the reaction when two colliding particles have the same (opposite) helicity. From Eq. 1 and equating the cross section to the ratio of experimental yield (N) and the integrated luminosity (L), A_{LL} is expressed as

$$A_{LL} = \frac{1}{|P_B P_Y|} \cdot \frac{N_{++} - R_{LL} \cdot N_{+-}}{N_{++} + R_{LL} \cdot N_{+-}}; \quad R_{LL} = \frac{L_{++}}{L_{+-}}, \tag{2}$$

where $P_{Y(B)}$ are the polarizations of the RHIC "yellow" ("blue") beams.

PHENIX has already presented and published first A_{LL} data for inclusive π^0 production from the 2003/2004 RHIC runs (Run3/Run4) [14]. The results are shown on Fig. 1(left). Two theoretical curves based on NLO pQCD represent different assumptions for the gluon polarization [11,15]. The gluon polarization contributes to A_{LL} through gluon-gluon and gluon-quark subprocesses, with the gluon-gluon contribution significantly larger at mid-rapidity and for the estimated gluon momentum fraction for these results $x \approx 0.03-0.1$ [12]. The results are consistent with zero or small gluon polarization, with a confidence level (CL) of 21–24% for GRSV-std, for the range in polarization scale uncertainty of the measurement. The results are less consistent with a large gluon polarization, with CL=0–6% for GRSV-max.

Fig. 1(right) compares results obtained by HERMES, SMC and COMPASS collaborations to the same theoretical models. They constrain the possible gluon polarization in the proton through semi-inclusive measurements of two hadrons to utilize the photon-gluon fusion process [3]. HERMES result sensitivity in its kinematic range is not yet enough to distinguish between GRSV-std and GRSV-max models, while SMC (probing the same x_g as PHENIX) and COMPASS points, similar to the PHENIX result, favor more the GRSV-std calculation.

Even with a small integrated luminosity (220 nb^{-1} in Run3 and 75 nb^{-1} in Run4) and moderate beam polarization ($\sim$27% in Run3 and $\sim$40% in Run4) PHENIX data have already started constraining Δg at a level comparable to polarized-DIS data. The increased integrated luminosity and improved polarization expected for the on-going Run5 should provide an order of magnitude decrease in statistical uncertainties.

Prompt photons (γ^{prompt}) are considered as the "golden" probe for Δg due to the dominance of Gluon Compton graph in γ^{prompt} production [13]. Measurement of $A_{LL}(\gamma^{prompt})$ requires considerable integrated luminosity. The results from 70% polarized proton beam collisions corresponding to $\sim 200\ pb^{-1}$ are expected in 2007-2008.

2.2 Antiquark polarization

Detailed flavor analysis is possible with $W^{\pm}$ production measurements, since the participating quark and antiquark helicities are fixed and the dominant contributors are u, d, $\bar{u}$ and $\bar{d}$: $u\bar{d} \rightarrow$

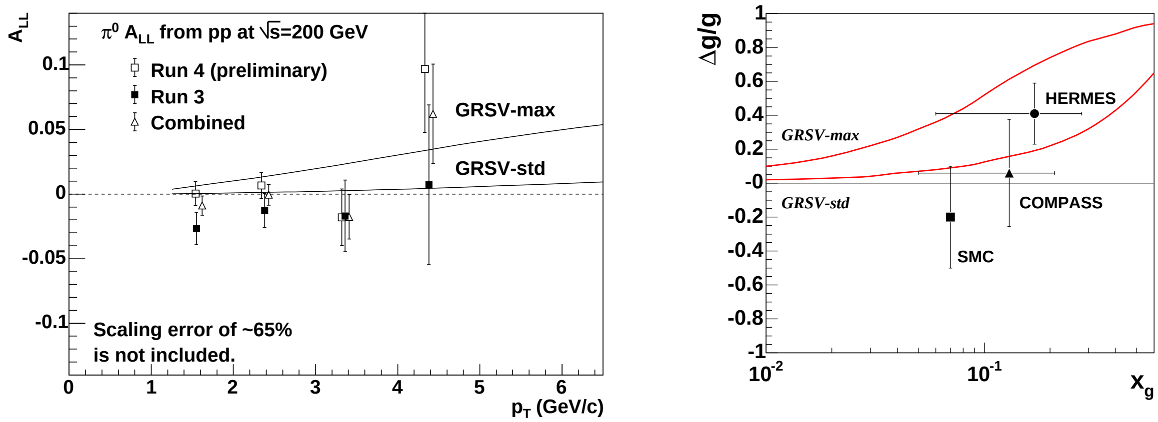

Figure 1: Left: $A_{LL}^{\pi^0}$ versus mean p_T of π^0's in each bin; a scale uncertainty of $\pm 65\%$ is not included. Two theoretical calculations based on NLO pQCD are also shown for comparison with the data. Right: HERMES, SMC and COMPASS results compared to the same theoretical calculations.

W^+, $d\bar{u} \to W^-$. The parity violating longitudinal single-spin asymmetry is

$$A_L = -\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}, \tag{3}$$

where σ_+ (σ_-) represents a cross section of the reaction with the initial proton helicity "+" ("−"), protons from the other beam being unpolarized (or helicity states averaged). For W^- production

$$A_L^{W^-} = \frac{\Delta d(x_1)\bar{u}(x_2) - \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}. \tag{4}$$

To obtain the asymmetry for W^+, one has to interchange u and d in Eq. 4. At large x_2, where $\bar{u}(x_2)$ is small, $A_L^{W^-}$ becomes $-\Delta\bar{u}/\bar{u}$, and at large x_1, $A_L^{W^-}$ is $\Delta d/d$. Likewise from W^+, $\Delta\bar{d}/\bar{d}$ and $\Delta u/u$ can be extracted.

In the central arms $W^\pm$ are identified as a Jacobian peak in the p_T spectrum of electrons and positrons. In the muon arms the p_T spectrum of muons is predominantly from $W^\pm$ decays for the p_T region above 20 GeV/c. First results on $A_L^{W^\pm}$ from longitudinally polarized pp collisions at $\sqrt{s}$=500 GeV are expected in 2009-2010.

2.3 *Transverse spin*

Exciting physics prospects also arise for transverse polarization of the RHIC proton beams. One is the possibility of a first measurement of the quark transversity densities δq. Difference between Δq and δq provide a measure of the relativistic nature of quarks inside the nucleon.

Studies of transverse single-spin asymmetries (A_N) is a further interesting application. Similarly to A_{LL} (Eq. 2), A_N is experimentally defined:

$$A_N = \frac{1}{|P|} \cdot \frac{1}{\langle|cos\phi|\rangle} \cdot \frac{N_\uparrow - R_N \cdot N_\downarrow}{N_\uparrow + R_N \cdot N_\downarrow}; \quad R_N = \frac{L_\uparrow}{L_\downarrow}, \tag{5}$$

where we compare particle production on the left side of upward and downward polarized beam; $\langle|cos\phi|\rangle$ is the average $|cos\phi|$ of the detected particles, with ϕ the azimuthal angle.

Over the years, a number of models based on pQCD have been developed to explain the asymmetries observed at lower energies. Among them are the Sivers effect [16], transversity and the Collins effect [17], and various models which attribute the observed asymmetries to higher twist contributions (e.g. [18]).

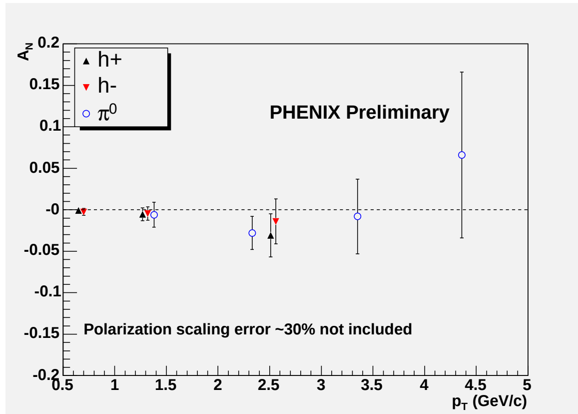

Figure 2: Transverse single spin asymmetry for inclusive charged hadrons and neutral pions; a scale uncertainty of ±30% is not included.

Fig. 2 shows the A_N in π^0 and charged hadron production vs p_T. The transverse single-spin asymmetries are consistent with zero over the measured transverse momentum range. A small or zero asymmetry in this kinematic region follows the trend of previous results, which indicate a decreasing asymmetry at decreasing x_F [19,7].

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